A large, colorful map of the Cosmic Microwave Background (CMB) fluctuations, showing a complex pattern of blue and orange/red spots, representing temperature variations across the sky. The map is partially obscured by the title text.

Planck constraints on Cosmic Birefringence and its cross-correlation with the CMB

Based on **G.Zagatti**, M. Bortolami, A. Gruppuso, P. Natoli,
L. Pagano, G. Fabbian (<https://arxiv.org/abs/2401.11973>)

$$\mathcal{L}_{em} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{\lambda}{4f} \phi F_{\mu\nu} \tilde{F}^{\mu\nu} \rightarrow \text{Parity-violating term}$$

Modified electromagnetic Lagrangian



Modified Maxwell equations

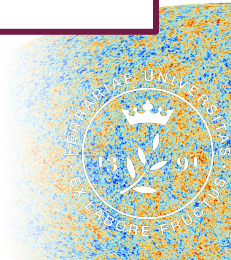


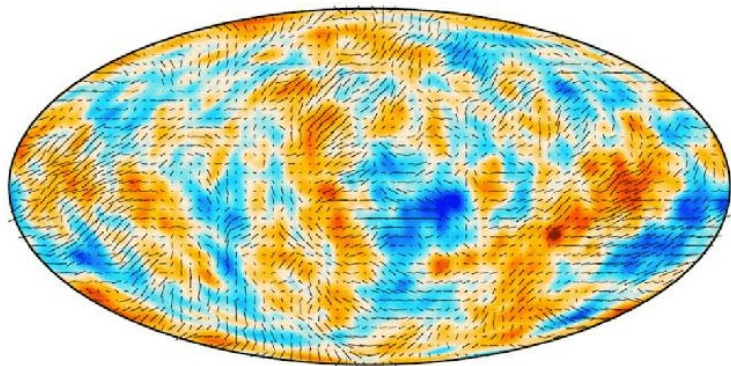
Modified wave equation



Different dispersion relations for right- and left-handed circularly polarized photons

Cumulative and
frequency-independent
rotation of the polarization
plane of **linearly polarized**
radiation





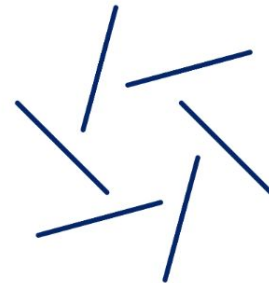
$$P = \sum_{l=2}^{+\infty} \sum_{m=-l}^{+l} [a_{lm}^E Y_{lm}^E + a_{lm}^B Y_{lm}^B]$$

E-modes



Parity even

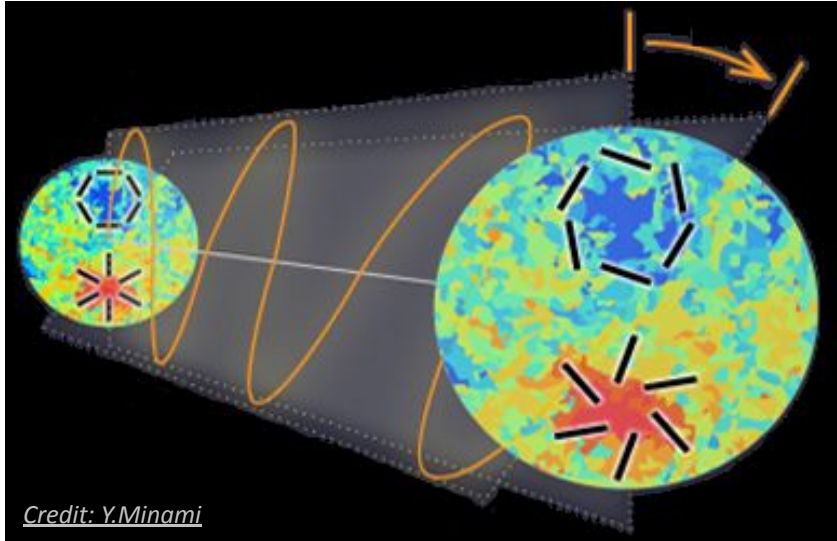
B-modes



Parity odd

$$\langle EB \rangle = \langle TB \rangle = 0$$





$$\alpha(\hat{n}) = \sum_{LM} \alpha_{LM} Y_{LM}(\hat{n})$$

Rotation induced E- and B-modes

$$a_{\ell m}^{B,tot} = a_{\ell m}^B + \delta a_{\ell m}^B$$

$$a_{\ell m}^{E,tot} = a_{\ell m}^E + \delta a_{\ell m}^E$$

$$\langle EB \rangle \neq 0$$

$$\langle TB \rangle \neq 0$$



- Relation between the parity-violating EB cross-correlation and the CB field

$$\langle a_{\ell m}^{E,tot} a_{\ell' m'}^{B,tot,*} \rangle = 2 \sum_{LM} \alpha_{LM} C_{\ell}^{EE} H_{\ell \ell'}^L \xi_{\ell \ell' m m'}^{LM}$$

- Estimate of the α_{LM} coefficients

Inverse variance weighting average

$$\bar{\alpha}_{LM} \propto \frac{1}{\sigma_L^{-2}} \sum_{\ell \ell' m m'} a_{\ell m}^{E,obs} a_{\ell' m'}^{B,obs,*} K_{\ell \ell' m m'}^{LM}$$

Biased estimate of the spherical harmonic coefficients of the CB field due to:

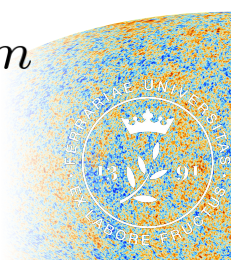
- ❑ mask effects
- ❑ not homogeneous noise
- ❑ other signals

Required a **debiasing** procedure

$$\hat{\alpha}_{LM} = \bar{\alpha}_{LM} - \alpha_{LM}^{MF}$$

Mean Field bias, evaluated over simulations

$$\alpha_{LM}^{MF} = \langle \bar{\alpha}_{LM} \rangle_{sim}$$



^[1] V. Gluscevic et al. (2012)

$$C_L^{\hat{\alpha}\hat{\alpha}} = \frac{1}{f_{sky}} \frac{1}{2L+1} \sum_M \hat{\alpha}_{LM} \hat{\alpha}_{LM}^*$$

$$\bar{\alpha}_{LM} \propto \frac{1}{\sigma_L^{-2}} \sum_{\ell\ell'mm'} a_{\ell m}^{E,obs} a_{\ell' m'}^{B,obs,*} K_{\ell\ell'mm'}^{LM}$$

Biased estimate of the Cosmic Birefringence power spectrum

- ❑ $\ell = \ell'$ signal
- ❑ $\ell \neq \ell'$ signal from:
 - ❑ cut sky
 - ❑ not homogeneous noise
 - ❑ lensing

! CB signature: $\ell \neq \ell'$

Required **debiasing** procedure ^[1]

$$C_L^{bias} = C_L^{bias,iso} + C_L^{bias,MC}$$

Analytic term evaluated from **data**

Bias term based on Monte Carlo **simulations**

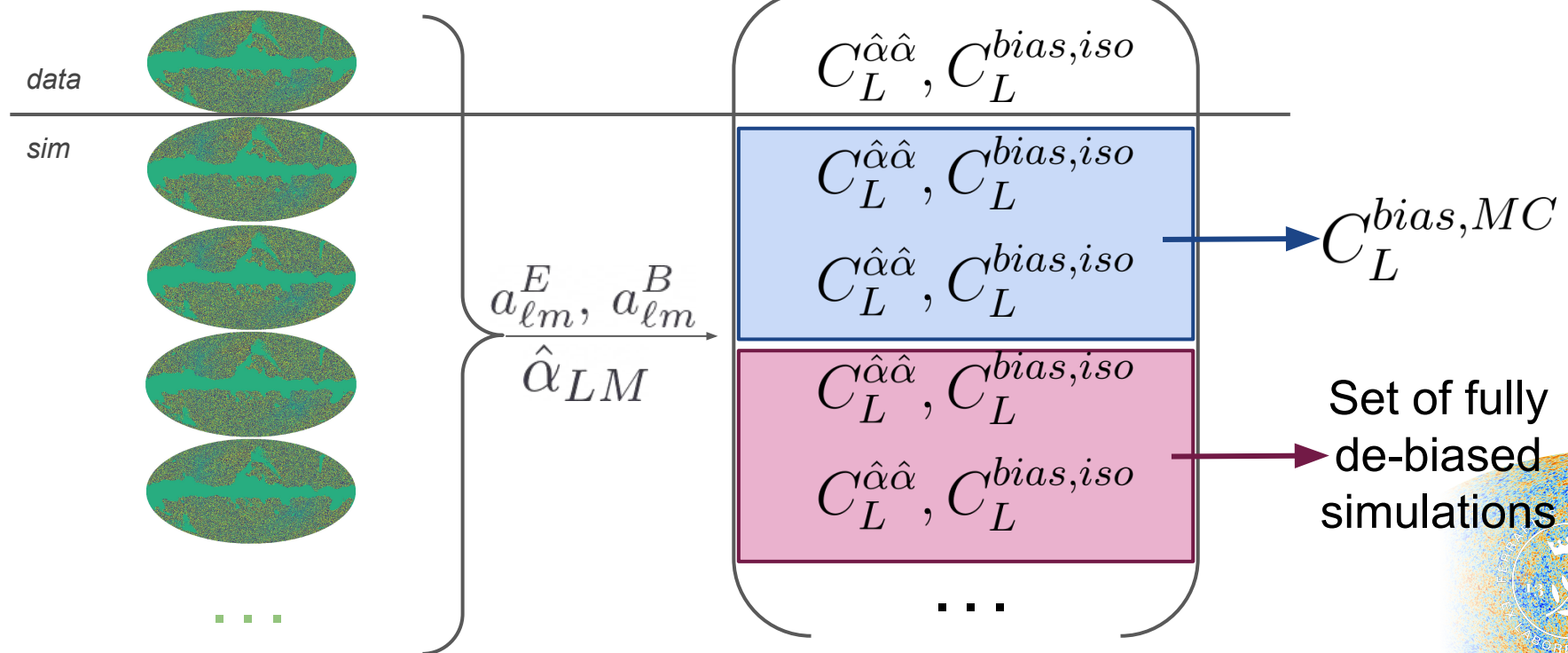
$$\hat{C}_L^{\alpha\alpha} = C_L^{\hat{\alpha}\hat{\alpha}} - C_L^{bias}$$

^[1] V. Gluscevic et al. (2012)



CMB + noise data and simulations, masked with the fiducial mask analysis

$$\hat{C}_L^{\alpha\alpha} = C_L^{\hat{\alpha}\hat{\alpha}} - C_L^{bias,iso} - C_L^{bias,MC}$$



- Planck CMB maps at the Healpix resolution of $NSIDE = 2048$
- CMB maps cleaned using the component separation commander ^[2]
- **Public Release 3** ^[3]: 300 CMB+noise simulations for half mission 1, half mission 2 and full mission data
- **Public Release 4** ^[4]: 400 CMB+noise simulations for data split A, B and full mission data

^[2] Planck collaboration IV

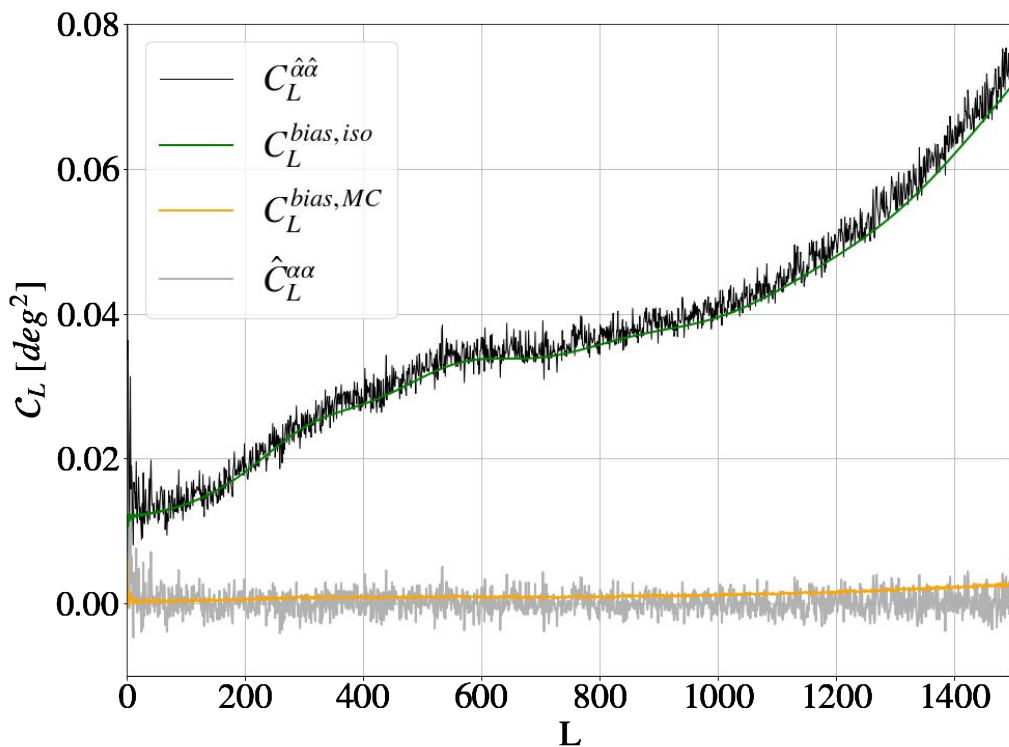
^[3] Planck collaboration I

^[4] Planck collaboration LVII

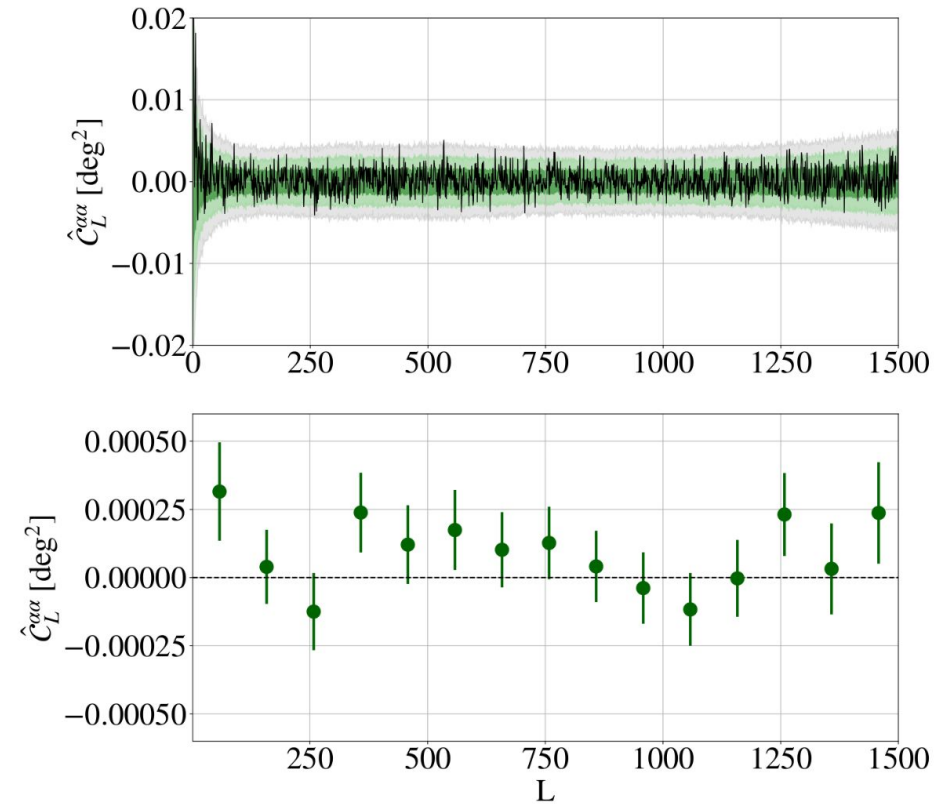


Full mission data

$$\hat{C}_L^{\alpha\alpha} = \underbrace{C_L^{\hat{\alpha}\hat{\alpha}}}_{\text{circled}} - C_L^{bias,iso} - C_L^{bias,MC}$$



Full mission data



- Cosmic Birefringence power spectra of both Planck data compatible with zero at 95% confidence level.
- Constraint on a scale invariant power spectrum in band powers:

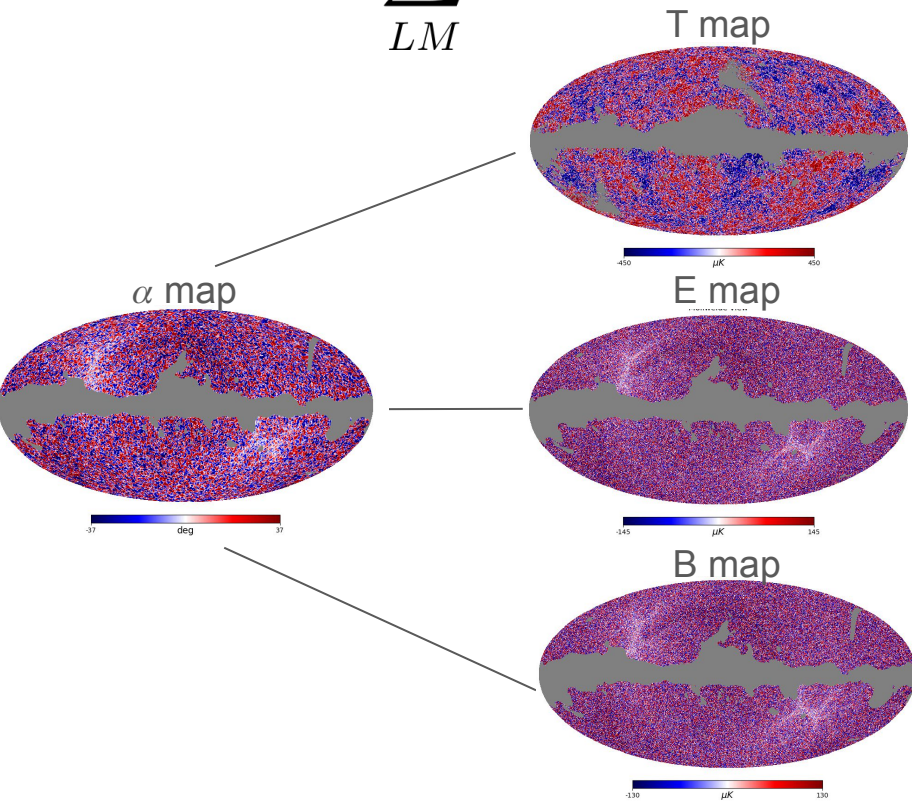
$$\mathcal{A}^{\alpha\alpha} \sim 9.9 \times 10^{-3} \text{deg}^2$$



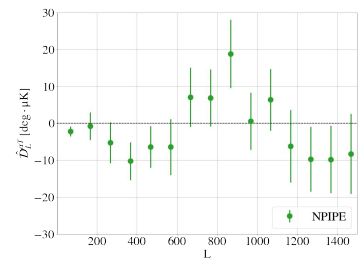
Map of the CB field

& CB-CMB cross correlations

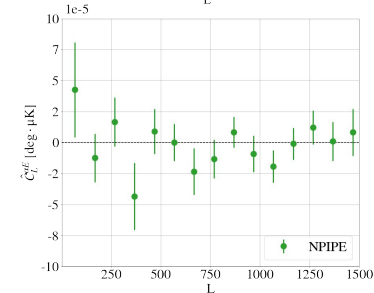
$$\alpha(\hat{n}) = \sum_{LM} \alpha_{LM} Y_{LM}(\hat{n})$$



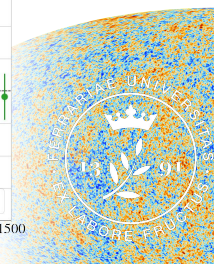
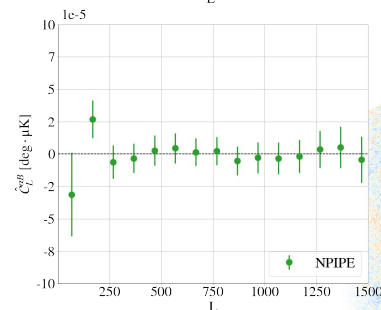
α T cross-spectrum



α E cross-spectrum



α B cross-spectrum

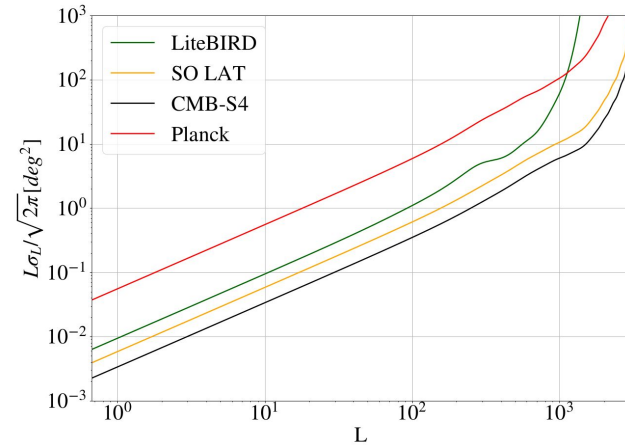


- Development of a pipeline to estimate the spherical harmonic coefficients of the Cosmic Birefringence field
- Application of the pipeline to Planck data products to obtain the CB power spectrum

| | NPIPE Commander | |
|----------------|-----------------|--|
| αT | 8.27% | |
| αE | 79.37% | |
| αB | 98.75% | |
| $\alpha\alpha$ | 84.85% | |

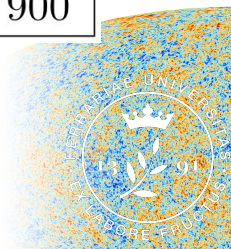
- CB-CMB cross-spectra

- Expected an improvement of almost a factor of 1000 in the next decade



| Improvements <i>wrt Planck</i> | |
|--------------------------------|-------|
| <i>LiteBIRD</i> | ~ 25 |
| <i>Simons Observatory LAT</i> | ~ 100 |
| <i>CMB-S4</i> | ~ 900 |

Planck sensitivity compared to forthcoming CMB experiments



Thank you

